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Enhancement of the Duty Cycle Cooperative Medium Access Control for Wireless Body Area Networks

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ABSTRACT This paper presents a novel energy-efficient and reliable connection to enhance the transmission of data over a shared medium for wireless body area networks (WBAN). We propose a novel protocol of two master nodes-based cooperative protocol. In the proposed protocol, two master nodes were considered, that is, the belt master node and the outer body master node. The master nodes work cooperatively to avoid the retransmission process by sensors due to fading and collision, reducing the bit error rate (BER), which results in a reduction of the duty cycle and average transmission power. In addition, we have also presented a mathematical model of the duty cycle with the proposed protocol for the WBAN. The results show that the proposed cooperative protocol reduced the BER by a factor of 4. The average transmission power is reduced by a factor of 0.21 and this shows the potential of the proposed technique to be used in future wearable wireless sensors and systems.

INDEX TERMS Wireless body area network, cooperative communication, duty cycle, bit error rate, average transmission power, energy efficiency.

I. INTRODUCTION

WBAN are communication networks of sensors (and/or actuators) placed on, inside, or perhaps around the body that represent a new generation of personal area networks and present different implementation challenges [1]–[6]. Sensors of WBAN are small, and they are embedded with a finite source, which is not the case for traditional wireless sensor networks (WSN). Finite batteries limit the energy available for the use of the sensor nodes in sensing, processing, storing, and sending data, and this directly affects the overall energy efficiency, the network's lifetime, the transmission rate, and the end-to-end delay of the WBAN [7], [8]. Thus, the energy efficiency of WBAN is a critical issue, and it must be addressed in any WBAN system [5].

The most suitable layers to deal with energy efficiency are the network layer (such as the routing technique) and the data link layer (such as a medium access control protocol). Medium access control (MAC) protocol controls and organizes nodes access to the shared wireless medium. MAC is an essential of any communication protocol stack used in any wireless network, which provides the basis for setting Quality of Service (QoS), a high data rate, end-to-end delay, reliability, and decreased energy. The essential task of the MAC protocol is to avoid both collisions. Therefore, all the above issues must be considered when designing MAC protocols.

The problem of saving energy in WBAN has been studied extensively [7]–[11]. Since the sensors usually are battery-powered, reducing the power consumption of the node to prolong the lifetime of the network is essential because the nodes are provided with a limited source of power. Retransmission data due to fading and collision is the primary source of wasted energy, so avoiding collisions is a technique that it is used to achieve better power efficiency [12]–[15].

Also, additional power can be saved by controlling the nodes' access to the shared wireless medium in the active mode of the superframe. The advantage of this approach is that it provides additional opportunities to save more power in the WBAN without having a negative impact on other important performance metrics [16], [17].

The diversity method is a technique used to combat the effect of fading of the wireless channel. Diversity can be done through the embedded sensors with multiple antennas or utilizing a cooperative communication [18], [19]. Nevertheless, such cooperative communication utilizes extra sub-channels/time slots to transmit a single data symbol from the source to the receiver that reduces the bandwidth efficiency of wireless channels [20], [21].

Different cooperative communications were considered for WBAN to improve their energy efficiency, reliability, and end-to-end delay. In [22], Deepak and Babu investigated the energy efficiency of an incremental relay-based cooperative communication in WBAN, they considered two communication model, the in-body communication between implant sensors and the gateway, and on-body communication between a body surface node and the gateway with line-of-sight (LOS) and non-LOS channels. In [23], Manirabona *et al.* proposed a Decode and Merge method which maintains the relaying mode by merging frames from relayed and relaying nodes. The throughput has been studied with keeping the energy consumption unchanged. In [24], Esteves *et al.* introduced a cooperative MAC protocol, named cooperative energy harvesting (CEH)-MAC, that adapts its operation to the energy harvesting (EH) conditions in WBAN. In [25], Link-Aware and Energy Efficient protocol for WBAN (LAEEBA) and Cooperative Link-Aware and Energy Efficient protocol for WBAN (CoLAEEBA) routing protocols are presented, they have investigated the throughput and the network lifetime. In [26], Ahmed *et al.* introduced a cooperative compressed sensing (CCS) approach, which takes into account the energy efficiency of WBAN by exploiting the benefits of random linear network coding (RLNC). Hiep *et al.* [27] analyzed and investigated the performance of multiple-hops in WBAN that was based on the IEEE 802.15.6 standard. The authors analyzed the performance of multiple-hops in WBAN, which include multiple node sensors and have many hops according to the power transmitted, the distance between the sensors, and the distance between the sensors and the coordinator. The proposed technique considered the power consumption and compared their protocol with the star-topology scenario. Rout and Das [28] developed a multi-relay, Ultra-Wideband (UWB)-based BAN system. Theoretical and simulation results based on IEEE 802.15.6 with a CM3 channel model were analyzed and discussed. The work generally focused on the study of Amplify-and-Forward (AF) and Decode-and-Forward (DF) relaying and direct transmission for WBAN in the 3.1 - 10.6 GHz UWB band. In [29], Yousaf *et al.* proposed proactive relays selection for both on-body and in-body WBAN. The results showed that a three-relay, incremental cooperative communication performed better in terms of the probability error rate (PER). In [30], Cui *et al.* proposed a joint relay selection and power control scheme (JRP) that taking into account transmission reliability. The proposed protocol achieved a good trade-off between reliability and energy consumption. However, the disadvantage of the multi-hop and cooperative communication, as presented in [22]–[30] is that the on-body sensor nodes must retransmit the other sensors' data in the case of data packet losses, where these nodes may need to transmit twice, i.e., it must transmit its own data and the data of other sensors. This retransmission mechanism results in a reduction of the energy efficiency of the on-body sensors since more energy is consumed in retransmitting the data of other sensors to the destination (gateway). A comparison of the state-of-the-art work is also shown in Table 1. Our proposed protocol concerned with how to improve the reliability of the communication between on-body sensors, and coordinators.

The limitations of the proposed protocols in [22]–[30] can be elaborated as follows: 1) The relay nodes in the cooperative communication are sensors and they are involved in the retransmitting of the data of other sensors, which reduces the overall energy of WBAN. 2) When the sensors are involved in cooperation, they may have to transmit twice, once for their own data and once for the other sensors' data. In doing so, the probability of collisions increases, and retransmissions occur, which increases the duty cycles and reduces the energy efficiency of the other sensors. 3) In the WBAN, it is possible that not all sensors have data to transmit in the wakeup period, so involving these sensors in relaying may increase competition, thereby increasing the duty cycles and reducing the energy efficiency.

However, to the best of our knowledge, none of the previous work utilized two master nodes architecture. In this paper, we present Two Master Nodes Cooperative Protocol (TMNCP) based on IEEE 802.15.6 CSMA policy. The contributions of this paper are summarized as follows:

1) We propose incremental cooperative communication that involves master nodes in relaying the data of the sensors instead of other on-body sensors.
2) The belt master node performs all retransmission and cooperation issues, which reduces competition between sensors and lessens the probability of collisions, consequently improving energy efficiency.
3) The master nodes are embedded with double transceivers, one of them is used for communication with the sensors and the other transceiver is used for communication between master nodes. Thus, it is unnecessary to leave time for the master nodes in the time frame, and this reduces the active time of the sensor significantly, also reduces competition between sensors. In addition, the TMNCP does not require a significant change in WBAN 802.15.6 standard and it can be considered as plug and play protocol.
4) We derived the BER of the proposed protocol by taking into account two types of channels, i.e., small-scale and shadowing models. We demonstrated that the proposed

TABLE 1. **Comparison of state-of-art work.**

Ref.	Proposed Protocol	Enhancement	Limitations
[22]	Incremental Relay based Cooperative Communications	• Improves the energy efficiency significantly • Optimal packet size	• It burdens sensors nodes in the retransmission process and increases their transmission power • Reliability is not considered
[23]	Decode and Merge technique (DMT)	• Interference mitigation • Throughput • Residual energy	• Number of the nodes is not considered
[24]	Cooperative Energy Harvesting (CEH)-MAC	• Network throughput • Average end-to-end delay • Energy efficiency	• It burdens sensors nodes in the retransmission process and increases their transmission power • Delay and reliability are not considered
[25]	Cooperative Link aware and Energy Efficient (Co-LAEEBA) Protocol	• Residual energy increases • Throughput • Prolong network lifetime	• Does not consider MAC protocol in their analysis • Delay is not considered
[26]	Cooperative Compressed Sensing (CCS)	• The energy efficiency of the body sensor nodes • Low complexity reconstruction algorithm, namely De-correlated Iterative Reweighed Group LASSO (DIG LASSO)	• It burdens sensors nodes in the retransmission process and increases their transmission power • Delay is not analyzed • MAC protocol is not considered (IEEE 802.15.6)
[27]	Multi-hop relaying technique	• Improves network throughput by exploiting multi-hops communications, • Achieves high-energy efficiency by reducing the transmission power	• Not suitable for large-scale networks
[28]	Multi-relaying for UWB	• Bit error rate • Power efficiency	• MAC protocol is not considered (IEEE 802.15.6) • It burdens sensors nodes in the retransmission process
[29]	Incremental Cooperative Critical Data Transmission in Emergences For Static WBAN (InCo-CEStat)	• Improve the reliability • Residual energy increases • Improve throughput	• MAC protocol is not considered (IEEE 802.15.6) • It burdens sensors nodes in the retransmission process and increases their transmission power
[30]	A joint relay selection and power control scheme (JRP)	• Improve transmission reliability • Average throughput improved	• It burdens sensors nodes in the retransmission process and increases their transmission power • MAC is not considered
Proposed work 2018	Two Master node Cooperative Protocol (TMNCP)	• Duty cycle • Bit error rate • Power efficiency • Energy efficiency	• It does not burden sensors nodes in retransmission process • It considers delay, reliability and IEEE 802.15.6 standard

protocol has reduced duty cycle, average transmission power and achieve better energy efficiency.

The rest of the paper is organized as follows. The system model and the architecture of the proposed protocol are presented in Section 2. In Section 3, the proposed TMNCP is described in detail, including the investigation of Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) based on IEEE 802.15.6 and Duty Cycle and Power Analysis for CSMA/CA based on IEEE 802.15.6 and IEEE 802.15.6 TMNCP. The required parameters, a numerical example, and the analysis of the numerical are provided in Section 4. Section 5 presents our conclusions and the future work we have planned.

II. SYSTEM MODEL AND ARCHITECTURE

A. NETWORK ARCHITECTURE

The IoT (Internet of Things) health network topology states the arrangement of various components of an IoT healthcare network that shows representative scenarios of seamless healthcare environments. Figure 1 refers

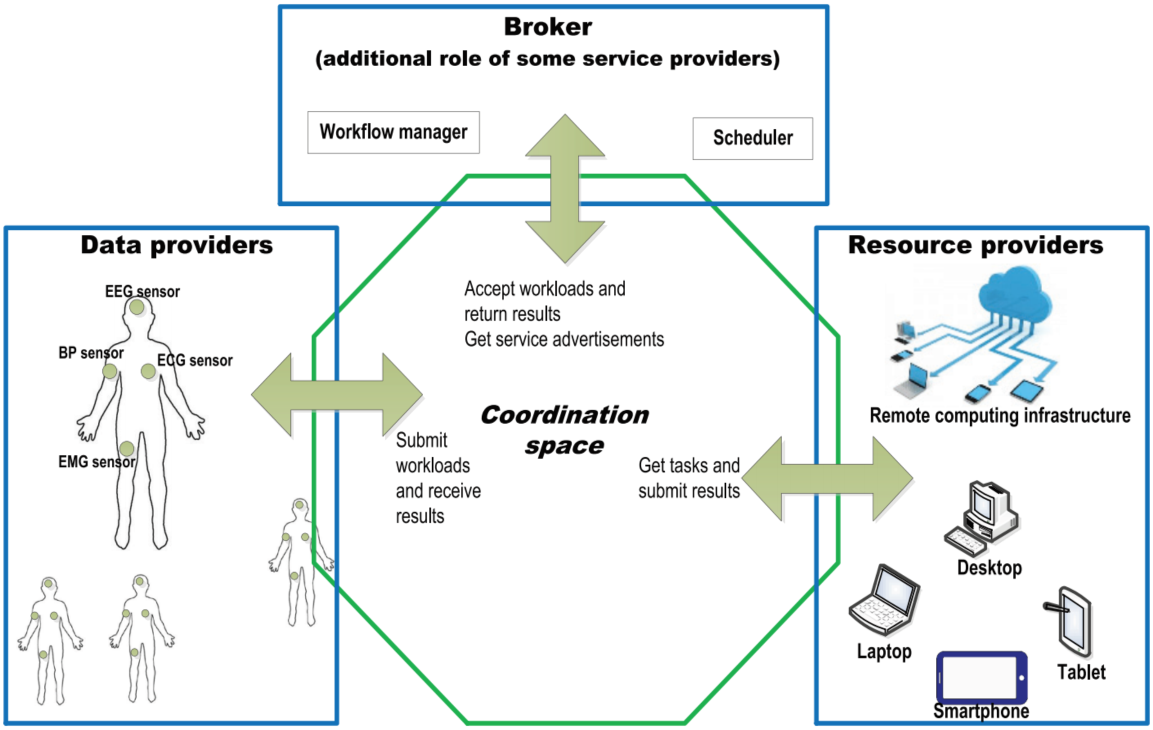

FIGURE 1. A conceptual diagram of IoT-based for healthcare [31].

to how a heterogeneous computing grid gathers massive amounts of vital signals and sensor data, for example, blood pressure (BP), body temperature, electrocardiograms (ECG), and oxygen saturation and forms a typical IoT Net topology. Vitals are taken using portable medical devices and sensors attached to his or her body. Taken data are then examined and stored, and stored data from different sensors and machines become useful for aggregation. Based on analyses, caregivers can see patients from any place and react accordingly [31].

An example of WBAN architecture is shown in Figure 2 and 3. Sensors are distributed over the surface of the body to gather health data, and sensors transmit the data to the coordinator for analysis. In a WBAN system based on the one-hop star topology, all sensors send their data to the coordinator. In such a scenario, the major causes of power losses in WBAN are, retransmission process due to fading and collisions, idle listening, overhearing, traffic fluctuations, and protocol overhead, the first two of which can be avoided partially or fully by utilizing two masters -slave topology.

In this paper, two masters – slave architecture is proposed. One of the master nodes is fixed on the body, such as a node carried around the belt, which is called the on-body master node (OBN). The other master node functions as a monitor and can receive data from the sensor nodes (slaves) as the carried node can, and it is referred to as the outer master node (OMN). Because of the movement of the body, the distances between the sensor nodes and two master nodes vary.

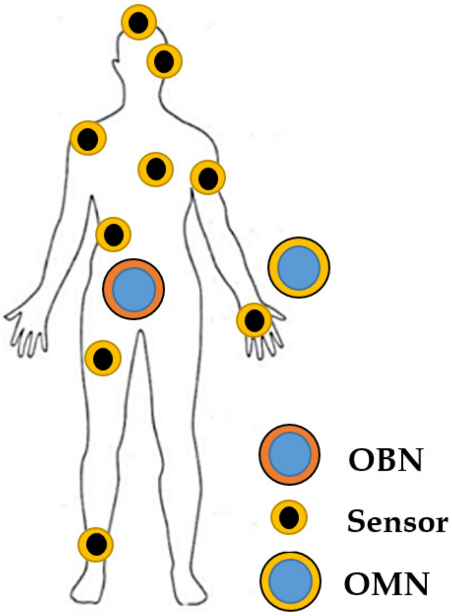

FIGURE 2. WBAN network architecture with two master nodes.

Some sensors may be located far away from the outer master node compared to the on-body master node and vice versa. Therefore, some sensors may have better channel quality with respect to the outer master node than to the on-body master node.

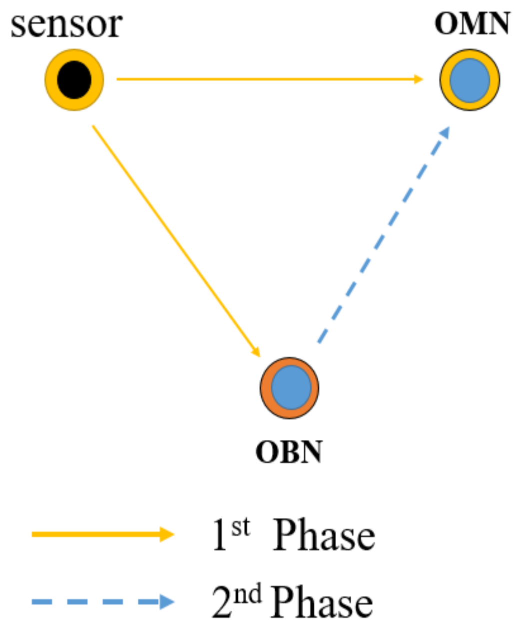

FIGURE 3. System model for WBAN cooperative communication.

The proposed protocol can significantly shift the retransmission process from the sensors to the master nodes. Hence, the energy efficiency of the sensors is increased.

B. COMMUNICATION MODEL OF TMNCP

The proposed protocol takes into consideration the principle of ARQ, and it works in a cooperative fashion, as follows: in the first phase, the sensor node broadcasts the data to the master nodes (on-body nodes and outer nodes). In the second phase, the OMN checks the received data to determine whether it has been received accurately; then the OMN sends back a positive ACK, and OBN drops the data that have been received from the sensor, as shown in Figure 3. Otherwise, the OMN sends NACK to the OBN, which re-sends the data received from the sensor to the OMN and then combines the signal data of the first and second phases via Maximal Ratio Combining (MRC).

The aims of this work are summarized as follows:

1) Improve the reliability of the received data: if the signal is not received correctly at the OMN, then the OBN retransmits the data received from the sensor to OMN, and OMN combines the received data (signals), thereby improving the quality of the data.
2) Efficient use of energy at the sensor and the OBN: if the data are received accurately at OMN, OBN does not have to retransmit the sensors' data which is happening in traditional WBAN communication system, thereby reducing the power consumption of OBN. If the data received at OMN is corrupted, the OBN retransmits an additional copy of the data to OMN that not involve sensors in the retransmission process, which is the most significant cause of energy drain in the WBAN sensors.

III. PROPOSED COOPERATIVE MAC PROTOCOL FOR WBAN

CSMA/CA and time-division multiple access (TDMA) are suitable MAC protocols for WSN. The performance of CSMA/CA and TDMA in terms of delay and power consumption is reported in [27]. Because multiple WBAN, and WBAN sensors, which frequently access, then leave the medium, may be placed in the same area and share the same transmission range, thus CSMA/CA is preferable to TDMA [32].

A. COOPERATIVE MAC PROTOCOL FOR WBAN

A cooperative MAC protocol is proposed in this subsection. Sensors in WBAN are distributed over a limited area, and they usually are equipped with limited source power. Due to the above limitation, it is necessary to have a coordinator node in WBAN, which usually is carried around the belt. A coordinator node usually is embedded with a larger source of power than the sensors are. This network topology can enhance the transmission power and reduce the transmission range for the sensors and for operative CSMA/CA control. In this work, we attempted to design the MAC protocol in order to take care of some important issues:

1) Reliability: The proposed protocol is a cooperative protocol, which lowers the probability of losing data by sending data over two independent paths.
2) Reduce the retransmission process due to fading and collision: retransmission process is one of the main factors that is draining the batteries in WBAN. This protocol overcomes this issue by using two-master nodes.
3) Energy efficiency: Since the OBN does retransmission on behalf of the sensors, the number of retransmissions can be reduced, and hence enhance the energy efficiency.

B. INVESTIGATION OF CSMA/CA BASED ON IEEE 802.15.6

In this work, CSMA/CA is incorporated in the proposed TMNCP, and the basic procedures of IEEE 802.15.6 are described in detail in [33]. In CSMA/CA, a back-off counter (BO) has a random value between 1 and CW, and $CW \in (CWmin, CWmax)$. The values of $CWmin$ and $CWmax$ vary depending on the user's priorities [33]. The sensor decreases their BO by one for each idle CSMA slot that has a duration equal to pCSMASlotLength and latterly denoted as T_s. If the BO is equal to zer0, the sensor sends the frame. If the channel is not free due to the frame is being sent from another node, the node locks its BO until the channel is idle. The CW is doubled for an even number of failures or number of retransmission retrying, and it is maximum value 7 [33].

C. ANALYSIS OF THE DUTY CYCLE AND POWER FOR CSMA/CA BASED ON IEEE 802.15.6

In this subsection, we address the duty cycle (DC) and power for the traditional slave-master topology of CSMA/CA based on IEEE 802.15.6. The average transmission power is related directly to the duty cycle. DC is defined as the ratio of the RF active time to the sleeping time multiplied by the factor ($1+PER$). DC is expressed as [9]:

$$DC = \frac{T_{active}}{T_{Sleep}}(1+PER) \tag{1}$$

where T_{active} is the RF activity time, which is given as [34]:

$$T_{active} = T_{on} + T_{CW} + T_{data} + T_{ACK} + 2T_{pSIFS} + 2T_{\alpha} \tag{2}$$

T_{CW} is average contention time and it is given as:

$$T_{CW} = 0.5\ CW.T_s \tag{3}$$

The required time to send a data is given as [34]:

$$T_{DATA} = T_P + T_{PHY} + T_{MAC} + T_{BODY} + T_{FCS}. \tag{4}$$

The acknowledgment sending time is given by:

$$T_{ACK} = T_P + T_{PHY} + T_{MAC} + T_{FCS}. \tag{5}$$

The average probability of error at the packet level at each hop is given as [35], [36]:

$$PER = 1 - (1 - BER)^{P_{lngth}} \tag{6}$$

The DC is given as:

$$DC = \frac{T_{on} + T_{CW} + T_{data} + T_{ACK} + 2T_{pSIFS} + 2\alpha.}{T_{sleep}} \times \left(2 - (1 - BER)^{P_{lngth}}\right) \tag{7}$$

The factor,($2 - (1 - BER)^{P_{lngth}}$), is taken into account, which shows how the BER influences DC. DC and the average transmission power are affected directly by the factor ($2 - (1 - BER)^{P_{lngth}}$).

The average transmission power, P_{av}, is obtained via multiplying DC, V_{dd}, and I_{act}, where V_{dd} is the radiofrequency (RF) of the module supply voltage, and I_{act} is RF average active current [9].

$$P_{av} = DC \times V_{dd} \times I_{active} \tag{8}$$

T_{Sleep} : Sleep time
T : Total time to transmit packet
T_s : CSMA slot length or pCSMASlotLength
T_c : Collision time, $T_c = T_{active}$
T_{on} : RF transceiver power-on start time
T_{CW} : Average back-off time
T_{data} : Time to transmit a data packet
T_{ACK} : Time to receive an *ACK*
PER: Packet Error Rate
BER : Bit Error Rate
α : Delay time
T_P : preamble time
T_{PHY} : physical header time
T_{MAC} : MAC header
T_{BODY} : MAC frame body time
T_{FCS} : frame check sequence time
τ : Transmission probability
P_{lngth} : Packet length

TABLE 2. CSMA/CA procedure as defined in the IEEE 802.15.6 standard.

```
Procedure Sensor Channel Access in WBAN
Require: CWmin, CWmax, BC, and R
begin
  $CWmin$ is minimum contention window
  $CWmax$ is the maximum contention window
  $BC$ is a backoff time varies from 1 $to$ $CWmin$
  $R$ is the Maximum number of retransmission retrying
  SENSOR has data to be sent over medium
  SET $CW$
  SET-BC random value between 1 $and$ $CW$
  SET $R$
  For i = R
    BC start decrement by one
    BC reach to Zero & Unlocked
      If the channel free
        Access Success, breaks for
      Endif
    If i = even
      $CW = 2 \times CW$
    Endif
    If CW=CWmax
      breaks for
    Endif
  Endfor
```

D. PROPOSED COOPERATIVE PROTOCOL FOR WBAN

The main goal of this paper is to evaluate the duty cycle and average transmission power utilizing the IEEE 802.15.6 standard with the proposed cooperative communication. CSMA/CA based on our proposed protocol, TMNCP, is explained as follows. The sensor nodes in the proposed protocol will not change their access algorithm to channel, but instead of the sensor transmitting directly to OBN, the sensor will broadcast the data to OBN and OMN, and this communication occurs in the first phase. Therefore, the sensor will obey the CSMA/CA algorithm provided in Table 2. After OBN and OMN received the data sent by the sensor, the OMN decodes the data. At second phase, if the data have been received correctly, the OMN transmits immediate Acknowledgment (ACK) to the sensors and OBN. Thus, the sensor and OBN know that the packet was delivered correctly, and OBN drops the data received from the sensor. However, if the sensor and OBN do not receive ACK or if the OMN does not decode the data sent by the sensor, the OMN sends a Negative Acknowledgment (N-ACK). The OBN retransmits the data that were received from the sensor in the first phase, and OMN sums the received data via MCR.

The question that must be answered concerns how the master nodes communicate with each other. In fact, there are different options for the communication between OBN and OMN. In this work, it is assumed the master nodes are embedded with double transceivers, one of them is used for communication with the sensors and the other transceiver is used for the communication between master nodes. Thus, it is unnecessary to leave time for OBN in the time frame, and this reduces the active time of the sensor significantly, also reduce competition between sensors. According to proposed protocol TMNCP, if the OMN does not receive the data from

TABLE 3. CSMA/CA description of TMNCP for WBAN.

```
Procedure Cooperative Communication b/n Sensor and Master Nodes
Require: N
begin
N is the number of sensors on the Human Body
SENSOR is accessing the medium utilizing CSMA/CA 802.15.6
    defined in Table II
For N
  Sensor broadcast the data at first phase to OBN & OMN
      If OBN decode the received signal correctly
          OBN keep silent
        Otherwise
          OBN transmit negative-ACK
    Endif
  Then, A second phase
    If OMN decode the received signal correctly
          OMN transmit I-ACK
      Otherwise
          OMN transmit negative-ACK
          OBN retransmit what received from the sensor to OMN
          OMN combined all received signals through MRC
    Endif
Endfor
```

the sensor correctly, the OBN use the second transceiver to retransmit the data to OMN. Table 3 describes the TMNCP.

It is expected that DC of OBN is increased, but the DC of the sensor is reduced or remains unchanged. The proposed protocol decreases the number of retransmissions by the sensor.

E. BER OF TMNCP

The main aim of TMNCP is to minimize the number of retransmissions by the sensor nodes by reducing BER, which has a direct effect on the duty cycle and the average transmission power of each node. The BER of the proposed protocol has two parts, i.e., 1) direct transmission between the sensor nodes and the master nodes, and 2) cooperative transmission, which occurs between the master nodes. The BER of the proposed protocol is given as:

$$BER_{DPSK}^{TMNCP} = \underbrace{\left(BER_{S,OBN}^{d} \cap BER_{S,OMN}^{d}\right)}_{First\ Phase} \cup \underbrace{\left(\left(1 - BER_{S,OMN}^{d}\right) \cap BER_{S,OBN}^{d} \cap BER_{OBN,OMN}^{coop}\right)}_{Second\ Phase} \tag{9}$$

The event of the two phases and the events in each phase are exclusively independent, so we can re-write (9) as:

$$BER_{DPSK}^{TMNCP} = \underbrace{\left(BER_{S,OBN}^{d} \cdot BER_{S,OMN}^{d}\right)}_{First\ Phase} + \underbrace{\left(\left(1 - BER_{S,OMN}^{d}\right) \cdot BER_{S,OBN}^{d} \cdot BER_{OBN,OMN}^{coop}\right)}_{Second\ Phase} \tag{10}$$

The modulation scheme used for the IEEE 802.15.6 standard is DPSK [33]. Therefore, the BER on the node j due to the transmission from the node i is given as [38]:

$$BER_{DPSK} = Q\left(2\gamma_{i,j}\left|a_{i,j}\right|^{2}\right) \cong \frac{1}{2}e^{-\left(\gamma_{i,j}\cdot\left|a_{i,j}\right|^{2}.10^{Z_{ij}}\right)} \tag{11}$$

where $\gamma_{i,j}$ is the signal-to-noise ratio (SNR) between sensors i and j; $\left|a_{i,j}\right|^{2} = d_{ij}^{-v}$ is the wireless channel gain; d is the distance between two nodes; and v is the path loss exponent, Z is represented by the shadowing model and it is component Gaussian random variable with zero mean and variance equal to σ_{ij}^{2}. In this work, we have two channels for communication, i.e., sensors to the OBN node, which is named as on-body communication channel. Then, the second possible path is sensors to OMN and OBN to OMN, which is named as off-body communication channel. The on-body communication, which is the first channel represented as the shadowing model, and the on-body to external device communication, which is the second possible channel, and it is represented as the Quasi-static channel model [37]. Taking into account the BER of DPSK, which is given in (11), we can rewrite (10) as:

$$\begin{aligned} BER_{DPSK}^{TMNCP} &= \frac{1}{4}\Bigg[\left(e^{-\left(\frac{\gamma_{S,OBN}}{d_{s,OBM}^{v}}10^{Z_{s.OBM}}+\gamma_{S,OMN}X_{S,OMN}^{2}\right)}\right) \\ &\quad + \left(\left(1-\frac{1}{2}e^{-\gamma_{S,OMN}X_{S,OMN}^{2}}\right)\cdot e^{\frac{-\gamma_{S,OBN}}{d_{s,OBM}^{v}}10^{Z_{s.OBN}}} \right. \\ &\quad \left. \cdot e^{-\left(\gamma_{S,OMN}X_{S,OMN}^{2}+\gamma_{OBN,OMN}X_{OBN,OMN}^{2}\right)}\right)\Bigg] \end{aligned} \tag{12}$$

where $\gamma_{S,OBN}$, $\gamma_{S,OMN}$ and $\gamma_{OBN,OMN}$ are the signal-to-noise ratios between the sensors and OBN, the sensors and OMN, and OBN and OMN, respectively. $Z_{S,OBM}$ is the channel gain between the sensors and OBN, which is represented by the shadowing model. The terms $X_{S,OMN}^{2}$ and $X_{OBM,OMN}^{2}$ are the channel gain from the sensors to OMN and from OBN to OMN, respectively, which are represented by the Quasi-static model, and it is an exponential random variable with a mean, $|a|^{2} = d^{-v}$, and a variance of unity. By inserting the (12) in (7), then inserting the new DC in (8), we can obtain the average transmission power of the proposed protocol.

F. ENRGY EFFICIENCY of TMNCP

The energy efficiency (Γ) is defined as the energy required to successfully transmit and receive bits without errors divided by the total energy required to transmit and receive bits successfully, and it is expressed as:

$$\Gamma = \frac{P_{lngth}\left(1 - BER_{DPSK}^{TMNCP}\right)E_{tr}}{E_{tr,data}^{TMNCP} + E_{tr,ACK/NACK}^{TMNCP}} \tag{13}$$

where E_{tr} is energy is $E_{tx} + P_{t}/R$; E_{tx} and E_{rx} are the energies required for the transmitter and receiver to transmit and receive one bit; P_{t} is the transmission power; and

TABLE 4. Comparison of the energy efficiency of TMNCP and the protocol proposed in [29].

Distance (m)	TMNCP	Protocol proposed in [29]
0.2	69%	22%
0.5	59%	11%
0.9	55%	0%

$E_{tr,data}^{TMNCP}$ is the total energy consumed in the transmission of a data packet with TMNCP. The term $E_{tr,data}^{TMNCP}$ is expressed as:

$$\begin{aligned} &E_{tr,clata}^{TMNCP} \\ &= P_{lngth}(E_{tx} + P_t/R) \underbrace{\left(BER_{S,OBN}^{d} \cdot BER_{S,OMN}^{d}\right)}_{First\ Phase} \\ &\quad + \underbrace{P_{lngth}E_{rx}\left((1 - BER_{S,OMN}^{d}) \cdot BER_{S,OBN}^{d} \cdot BER_{OBN,OMN}^{coop}\right)}_{Seconcl\ Phase} \end{aligned} \tag{14}$$

In Eq. (14), E_{tx} and E_{rx} are the energies required for the transmitter and receiver to transmit and receive one bit, respectively. The first phase represents energy consumption by the sensor to broadcast the packet from the sensor to OBN and OMN, and the second phase represents energy consumption by the sensor to transmit the packet from OBN to OMN, and the sensor will only overhear the packet from OBN. $E_{tr,ACK/NACK}^{TMNCP}$ is the total energy consumed in the transmission of ACK and NACK with TMNCP:

$$\begin{aligned} &E_{tr,ACK/NACK}^{TMNCP} \\ &= A_{ACK/NACK} \left((E_{rx}) \underbrace{\left(BER_{S,OBN}^{d} \cdot BER_{S,OMN}^{d}\right)}_{First\ Phase} \right. \\ &\quad \left. + \underbrace{(E_{rx})\left((1 - BER_{S,OMN}^{d}) \cdot BER_{S,OBN}^{d} BER_{OBN,OMN}^{coop}\right)}_{Seconcl\ Phase} \right) \end{aligned} \tag{15}$$

where $A_{ACK/NACK}$ is the size of ACK/NACK in bits. The first phase and second phase represent energy consumption due to the overheating of ACK/NACK by the source sensor. Inserting Eq. (14) and Eq. (15) into Eq. (13), we can obtain the energy efficiency of TMNCP. Table 4 shows that the TMNCP outperformed the incremental relay that was proposed in [29] in terms of the energy efficiency. The evaluation parameters used in the Table 4 are as follows: both E_{tx} and E_{rx} are 50 nJ/bit, $P_{lngth} = 500\ bits$, $A_{ACK/NACK} = 64\ bits$, $v = 4$, transmission rate $R_{ate} = 2\ Mbps$, the shadowing variance $\sigma_{s,OBM}^2 = 5\ dB$, and $P_t = 1000\ mW$.

The results show that TMNCP outperformed the protocol proposed in [29] in terms of energy efficiency, where, even for greater distance between the sensors, the TMNCP had better performance than was achieved in [29].

IV. NUMERICAL ANALYSIS FOR TMNCP IN WBAN

A. REQUIRED PARAMETERS AND NUMERICAL EXAMPLE

In this section, the numerical parameters and an example are described. The R_{ate} is 75.9 Kbps. RF transceiver power-on start time (in seconds) for AD7020: $T_{on} = 2\ ms$. The minimum of CW_{min} is 16 slots, and the maximum of CW_{max} is 64 slots. Hence, the average back-off time is given as $(CW_{min}T_s)/2$, where each CSMA slot length, $T_s, is 125\ \mu s$. The short interframe spacing time for CSMA/CA of 802.15.6: $T_{PSIFS} = 50\ \mu s$. The payload of MAC frame (frame body) is 250 kB, and the time required to transmit 250 kB: $T_{body} = (250 \times 8)/(75.9 \times 1024) = 25.7\ ms$. The frame header and frame check sequences were 56 and 16 bits, respectively.

Then the $T_{MAC} = 56/(75.9 \times 1024) = 0.72\ ms$ and $T_{FCS} = 16/(75.9 \times 1024) = 0.205\ ms$. The time required to the physical header is 40 μs. The preamble bits are 88 bits, hence the time required to transmit 88 bits is $88/(75.9 \times 1024) = 1.13\ ms$. The delay time $\alpha = 1 \mu s$.

The BER parameters are explained here, and they depend on the signal-to-noise ratios, the distance, the shadowing model, and the quasi-fading components. The maximum distance between sensors and OBN was $1m$, then the path loss exponential, v, varied between 2 and 6, depending on the obstacles. In this work, we assumed that $v = 2$. The shadowing variance was varied between 0 and 12. Fading is an exponentially distributed random variable with the mean value $1/\delta$, and the average channel power was defined as $1/\delta = E[|Xij|^2] = d^{-v}$. For simplicity, the packet length was assumed to be 1. The duty cycle of the 802.15.6 standard using DPSK modulation is:

$$DC = \frac{T_{act}}{T_{sleep}} \left(2 - \left(1 - \frac{1}{2} e^{-\left(\gamma_{i,j} \cdot |a_{i,j}|^2\right)} \right)^{P_{lngth}} \right)$$

The $T_{act} = 2\ ms + 1\ ms + 27.795\ ms + 2.095\ ms + 0.1\ ms + 0.002\ ms = 32.992\ ms$, the $T_{sleep} = 1\ s$. The BER is 0.3645 of the DPSK for $\gamma_{i,j} = -5\ dB = 0.316$, and $1/\delta = d^{-v} = 1$. Hence, the duty cycle is:

$$\begin{aligned} DC &= \frac{32.992 \times 10^{-3}}{1\ s} \left(2 - (1 - 0.3645)^1 \right) \\ &= 45.02 \times 10^{-3} \end{aligned}$$

The average transmission power of the RF module supply voltage: $V_{dd} = 3\ v$ and the RF average active current: $I_{act} = 15.05\ mA$.

$$\begin{aligned} P_{avg} &= DC \times V_{dd} \times I_{act} \\ &= 45.02 \times 10^{-3} \times 3 \times 15.05 \times 10^{-3} \\ &= 2.03\ mW \end{aligned}$$

Now, let's examine the average transmission power of the proposed protocol. The active time and sleep time do not change, hence, $T_{act} = 32.992 ms$, and the sleep time is $1s$. The $d_{s,OBM}^{v} = 1$ for $v = 2$, $d_{s,OMN}^{v} = 4$ for $v = 2$, and $d_{OBM,OMN}^{v} = 1$ for $v = 2$. The shadowing variance $\sigma_{s,OBM}^2 = 5\ dB = 3.16$. The signal-to-noise ratios are assumed to be equal between links sensor-OBN, sensor-OMN, and OBN-OMN, which is $-5\ dB = 0.316$. The BER_{DPSK}^{TMNCP} is:

$$
\begin{aligned}
&BER_{DPSK}^{TMNCP}\\
&= \frac{1}{4}\left[\left(e^{-\left(\frac{0.316}{1^2}10^{0.5}+0.3162^{-2}\right)}\right)+\left(\left(1-\frac{1}{2}e^{-0.3162^{-2}}\right)\right.\right.\\
&\qquad \left.\left.\cdot e^{-\frac{0.316}{1^2}10^{0.5}}\cdot e^{-\left(\frac{0.316}{1^2}10^{0.5}+0.3161^{-2}\right)}\right)\right]\\
&= 0.25\,(0.34 + 0.0759\times 0.368 \times 0.268) = 0.08
\end{aligned}
$$

therefore, the duty cycle is:

$$
\begin{aligned}
DC_{TMNCP} &= \frac{32.992\times 10^{-3}}{1\ s}\left(2-(1-0.08)^{1}\right)\\
&= 35.63\times 10^{-3}
\end{aligned}
$$

Then, the average transmission power is:

$$
\begin{aligned}
P_{avg}^{TMNCP} &= DC_{TMNCP}\times V_{dd}\times I_{act}\\
&= 35.63\times 10^{-3}\times 3\times 15.05\times 10^{-3} = 1.6\ mW
\end{aligned}
$$

It is observed an increase by a factor of 0.21 was achieved by our proposed protocol.

B. NUMERICAL RESULTS AND DISCUSSION

In this subsection, the performance of the TMNCP protocol is evaluated in terms of BER, duty cycle, and average transmission power. In the evaluation, we assumed the same SNR from the sensors to OBN, OBN to OMN, and sensors to OMN, while the distances between nodes were assumed to be different.

Figure 4 shows a comparison of BER of the direct transmission 802.15.6 standard and TMNCP for difference normalized distances of $d_{SOBN} = \{0.5, 0.75, 1\}$ and $d_{SOMN} = \{0.5, 0.75, 2\}$ over varying SNR, i.e., {-5, -4, -3…, 5}. The important results that can be seen in the figure are summarized as follows:

1) The direct transmission had less performance compared to TMNCP, where BERs appeared less for TMNCP.
2) At $\sigma_{SOBN} = 5dB$, the BER is high compared to $\sigma_{SOBN} = 7dB$ and $9dB$ for TMNCP.
3) The BERs of TMNCP decreased as the distances between the nodes decreased.
4) At high SNR and at $\sigma_{SOBN} = 9dB$, the BER of the TMNCP has better performance compared to the direct transmission.
5) At low SNR and at $\sigma_{SOBN} = 5dB$ and $7dB$, the BER of the direct transmission approach the BER of TMNCP. However, At low SNR and at $\sigma_{SOBN} = 9dB$, the BER of TMNCP show better performance compared to the direct transmission.

Figure 5 shows the comparison of the DCs of direct transmission and TMNCP for difference-normalized distances of $d_{SOBN} = \{0.5, 0.75, 1\}$ and $d_{SOMN} = \{0.5, 0.75, 2\}$ over SNRs of $\{-5, -4, -3\ldots, 5\}$. The important results that can be seen in the figure are summarized as follows:

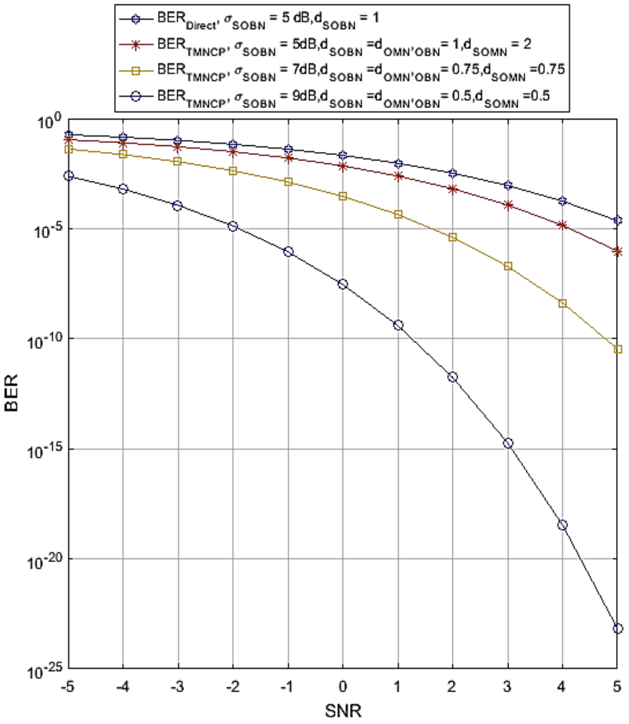

FIGURE 4. DPSK BER comparison against SNR for $v = 2$.

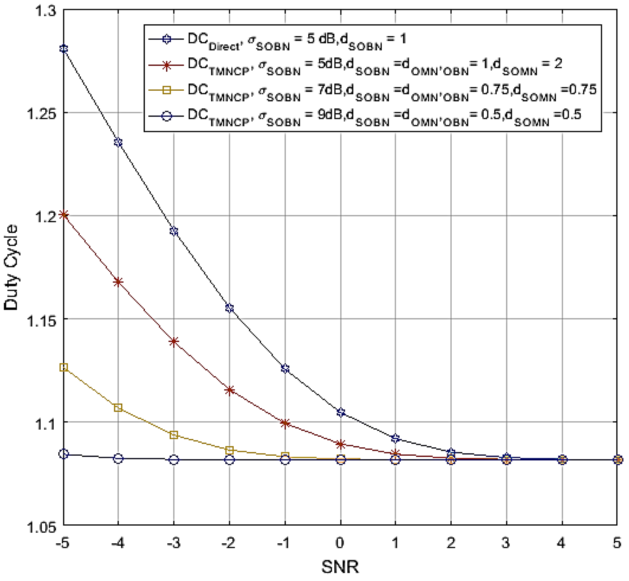

FIGURE 5. WBAN duty cycle comparison against SNR for $v = 2$.

1) The DCs of direct transmission were greater than the DCs of TMNCP because the proposed protocol had better performance in the term of BER than the direct transmissions that directly affect and reduce the DC.
2) When the sensors and the master nodes were close to each other, the duty cycles were reduced due to the distance between the nodes being less, which reduced the BER, that lead to a direct reduction in the duty cycle.
3) Larger shadowing parameters reduces the DCs because the shadowing variance improved the quality of the

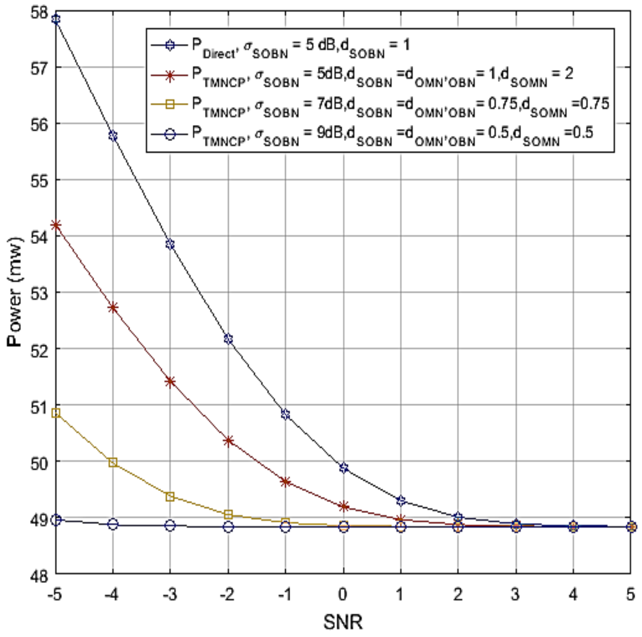

FIGURE 6. **Average transmission power comparison against SNR for $v = 2$.**

links and reduced BER, which consequently reduced the DCs.

4) At high SNR, the DCs of direct transmission and TMNCP are approximately the same.
5) At low SNR, the DCs of TMNCP have better performance compared to the DC of the direct transmission.

Figure 6 shows the comparison of average transmission power over SNR. It is clear that the average transmission power is less using the proposed protocol. The average transmission power was reduced more when the distances between the nodes were reduced and the shadowing variance increased. At SNR equal to -4 dB, the improvement achieved by the proposed protocol was 12.7% at the shadowing variance of 9 dB. However, the average transmission power of the proposed protocol and direct transmission are equal for the large SNR.

V. CONCLUSION

In this paper, we have presented a TMNCP that improved reliability, average transmission power, and energy efficiency of WBAN. TMNCP was transmitting the data over two independent paths with the help two master nodes. It is worked within two phases: a broadcast phase by which the on-body sensor transmitted the data to the master nodes, and the second phase where the master nodes cooperatively exchange data received from the sensor. TMNCP enabled two master nodes in WBAN systems which assisted the sensors to retransmit the corrupted data and hence enhanced their energy efficiency. The results showed that the proposed protocol is better than direct transmission when the distances between nodes are reduced and the shadowing variance is increased. It was also observed that the average transmission power was decreased by a factor of 0.21 when the TMNCP protocol was used. In addition, we have shown that the energy efficiency of TMNCP with respect to the proposed protocol of [29] is improved by factor of 0.69. Furthermore, the BER of the TMNCP is reduced by a factor of four compared to the direct transmission.

In future work, we will analyze the proposed protocol using a cognitive network that allows two different sensor nodes to use dynamic spectrum allocation that reduces competition on the single spectrum.

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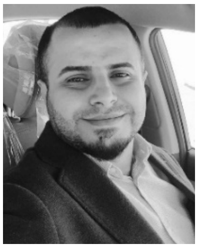

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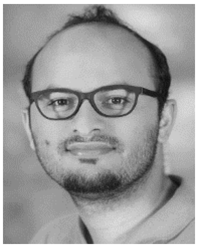

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